

**Summary of Research for NASA Grant NAG5-9227  
“Radial Velocity Detection of Extra-Solar Planetary Systems”**

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**(with a one year no-cost extension to 28 February 2004)**

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This NASA Origins Program grant supported four closely related research programs at The University of Texas at Austin: 1) The McDonald Observatory Planetary Search (MOPS) Program, using the McDonald Observatory 2.7m Harlan Smith telescope and its 2dcoudé spectrometer, 2) A high-precision radial-velocity survey of Hyades dwarfs, using the Keck telescope and its HIRES spectrograph, 3) A program at McDonald Observatory to obtain spectra of the parent stars of planetary systems at  $R = 210,000$ , and 4) the start of high precision radial velocity surveys using the Hobby-Eberly Telescope. The most important results from NASA support of these research programs are described below. A list of all papers published under support of this grant is included at the end.

### **The 2.7m McDonald Observatory Planetary Search (MOPS)**

During this grant, we obtained 9-10 observing runs per year of 4 nights each on the McDonald 2.7 m telescope with its 2dcoudé spectrograph. During the course of the grant, the MOPS target list grew from 140 stars to about 270 stars. Over the course of the grant, the MOPS 2.7 m survey discovered planetary companions to two bright stars:  $\epsilon$  Eridani (HR 1084) and  $\gamma$  Cephei (HR 8974).

#### **A planetary companion to $\epsilon$ Eridani.**

Walker *et al.* (1995), in their 12-year long RV survey of solar type stars, reported marginal evidence for RV variations which might be interpreted as indicating a Jovian analog around  $\epsilon$  Eri. Their RV measurements for this star varied with a period of 9.9 years and a semi-amplitude of  $15 \text{ ms}^{-1}$ . However, due to the low amplitude relative to the noise, and limited time base of the measurements, their result was not conclusive although it was strongly supported by the reanalysis of the Walker *et al.* data by Nelson and Angel (1998). We combined our MOPS data with the results of Walker *et al.*, and we obtained a very clear and significant orbital solution with a period of 6.9 years and an eccentricity of about 0.6. Addition of the data on this star from the Lick program (Cumming *et al.* 1999) very nicely confirms these results. We closely examined the Ca II H&K chromospheric emission data on  $\epsilon$  Eri (Baliunas, private communication), which is an excellent indicator of the magnetic activity cycle of the star. The Ca II data show a periodicity at about 3 years, and very little power at the radial velocity period of 6.9 years. Therefore, we believe the radial velocity variations are orbital in nature, and not a result of internal stellar variations. These results were published in Hatzes *et al.* (2000).

#### **A planetary companion to $\gamma$ Cephei.**

We later detected a planetary companion in orbit around the primary star of the binary system  $\gamma$  Cephei. We combined data from the McDonald MOPS Phases I, II, and III with the original CFHT data of Walker *et al.* (1995) to obtain a total data set spanning the interval 1981–2002. The data set revealed long-lived residual radial velocity variations (after subtracting the contribution due to the stellar companion) that were coherent in phase and amplitude with a period of 2.47 years and a semi-amplitude of  $27 \text{ ms}^{-1}$ . After a careful analysis of all the available photometric and spectroscopic data, we concluded that these residual radial velocity variations were most likely caused by a planetary mass companion with  $M \sin i = 1.59 M_{Jup}$  and an orbital semi-major axis of

$a_2 = 2.03\text{AU}$ , rather than by intrinsic stellar variability. Our Ca II H & K S-index measurements taken during 1998–2002 showed no variations with the planet period. Our McDonald Phase I data set consisted of high resolution ( $R = 200,000$ ) spectra suitable for line bisector measurements. Our analysis showed that the changes in the mean bisector velocity span and curvature for this star were less than  $5\text{ m s}^{-1}$ . The Hipparcos photometry for this star made during 1989–1992 was constant to less than 0.001 mag. An analysis of the CFHT Ca II  $\lambda 8662\text{Å}$  data showed that the possible long-period variations found by Walker *et al.* (1995) were only present during 1986.5–1992 and absent during 1981–1986.5. While these Ca II variations were not long-lived, as opposed to the radial velocity variations which have been completely stable in period and phase over 20 years, it was unlikely that rotation modulation was causing the radial velocity signal attributed to the planet. Furthermore, a refined period for the Ca II  $\lambda 8662\text{Å}$  variations was 2.1 yrs, significantly less than residual radial velocity period. The lack of Ca II, line bisector, and photometric variations for this star was inconsistent with the rotational modulation hypothesis for the residual RV variations and confirms the planet hypothesis first proposed by Walker *et al.* (1992). The long duration of our radial velocity measurements enabled us to obtain a better estimate of the binary period or  $P_{\text{Binary}} = 73.9 \pm 15.8\text{ yrs}$ .  $\gamma\text{ Cep}$  is the shortest period binary for which an extrasolar planet has been found and it may provide insights into the relationship between planetary and binary star formation. These results were published in Hatzes *et al.* (2003).

#### A brown-dwarf companion to HD 137510.

Since the beginning of precise Doppler surveys, one surprising enigma has emerged: the relative paucity of spectroscopic binaries where the secondary mass lies in between the stellar and planetary mass regime. This gap in the mass function for close-in ( $a \lesssim 4\text{ AU}$ ) companions to solar-type stars is often referred to as the “Brown Dwarf Desert”. Our 2.7m radial velocity survey has detected a companion to HD 137510 (G0IV), with a minimum mass of  $26\text{ M}_{\text{Jup}}$ . This brown dwarf companion to HD 137510 was also independently and simultaneously found by the Thüringer Landessternwarte Tautenburg (TLS) planet search program. HD 137510 (= HR 5740 = HIP 75535) is a bright ( $V = 6.3$ ) G-type star at a distance of  $41.75 \pm 1.7\text{ pc}$ . We performed a model atmosphere analysis of a high resolution, high SNR spectrum of HD 137510. We find that the star has a mass of  $M = 1.3 \pm 0.1\text{ M}_{\odot}$ , an effective temperature  $T_{\text{eff}} = 5896 \pm 57\text{ K}$ , a  $\log g$  of  $4.0 \pm 0.1$ , a radius  $R$  of  $1.9 \pm 0.2\text{ R}_{\odot}$ , an age of  $3.4 \pm 0.8\text{ Gyrs}$ , and  $[\text{Fe}/\text{H}] = 0.16 \pm 0.07\text{ dex}$ . The object is thus metal rich compared to the Sun. It thus appears that HD 137510 was a metal rich late F-type star which has now started its evolution away from the main sequence. Interestingly, Smith *et al.* (2001) noted that HD 137510 possibly underwent chemically fractioned accretion and represents a good candidate for having a close-in giant planetary companion. The combined McDonald and TLS data sets are best fit with an orbital period of  $798.2 \pm 1.4\text{ days}$ , a K velocity of  $531.6 \pm 5.3\text{ m s}^{-1}$ , and an eccentricity of  $0.402 \pm 0.008$ . The resulting mass function of this binary yields a minimum mass for the companion of  $26 \pm 1.4\text{ M}_{\text{Jup}}$ , and the semi-major axis is  $1.85 \pm 0.05\text{ AU}$ . These results were published in Endl *et al.* (2004).

#### A High-Precision Radial Velocity Survey of Hyades Dwarfs

From 1996 through 2003 we used the Keck 1 telescope with its HIRES spectrograph to conduct high precision radial velocity observations of a sample of 98 Hyades dwarf stars. The overall goals and methodology of the program are given by Cochran *et al.* 2002. The basic motivation for this program was that the Hyades represent a sample of stars of the same age and overall metallicity. This sample allows us to use an extremely homogeneous sample of stars to explore the dependence of the process of planet formation on only a single independent variable: the stellar mass.

We presented a summary of the Hyades planet search results in Paulson *et al.* (2004). In that papers, we also discussed the effects of stellar activity on radial velocity measurements. The level

of radial velocity scatter due to rotational modulation of stellar surface features for the Hyades was in agreement with the predictions of Saar and Donahue (1997) - the maximum radial velocity rms was up to  $\sim 50 \text{ m s}^{-1}$ , with an average rms of  $\sim 16 \text{ m s}^{-1}$ . In this sample of 94 stars, we found one new binary stellar system, two stars with linear trends indicative of binary companions, and no close-in giant planets. We discussed the limits on extrasolar planet detection in the Hyades and the constraints imposed on radial velocity surveys of young stars.

Due to their youth, Hyades members are much more chromospherically active than stars traditionally surveyed for planets using high precision radial velocity techniques. Therefore, we conducted a detailed investigation of the degree to which magnetic activity of our Hyades target stars interferes with our ability to make precise radial velocity searches for substellar companions. These results are given in Paulson *et al.* (2002). We measured chromospheric activity (which we took as a proxy for magnetic activity) by computing the equivalent of the  $R'_{\text{HK}}$  activity index from the Ca II K line. We examined correlations between simultaneously measured  $R'_{\text{HK}}$  and radial velocities and found that there is a significant correlation between  $R'_{\text{HK}}$  and the radial velocity in only 5 of the 82 stars in this sample. We concluded that this implies *long timescale* activity variations (of order a few years; i.e., magnetic cycles or growth and decay of plage regions) did not significantly hinder our search for planets in the Hyades if the stars are closely monitored for chromospheric activity. The trends in the radial velocity scatter ( $\sigma'_v$ ) with  $\langle R'_{\text{HK}} \rangle$ ,  $v \sin i$ , and  $P_{\text{rot}}$  for our stars was generally consistent with those found in field stars in the Lick planet search data. We selected four stars from our Hyades sample which showed significant radial velocity variability on short timescales to search for short-period planetary companions. The radial velocities of these four stars were monitored regularly with the HET for approximately two months; we also obtained near-simultaneous photometric observations with one of the automatic photoelectric telescopes at Fairborn Observatory. For three of the stars, we detected photometric variability with the same period present in the radial velocity measurements, compatible with the expected rotation rates for Hyades members. The fourth star continued to show  $v_r$  variations and minimal photometric variability but with no significant periodicity. This showed that for the three stars with periodic behavior, a significant portion of the observed  $v_r$  fluctuations were likely due primarily to magnetic activity modulated by stellar rotation rather than planetary companions. Thus, simultaneous monitoring of photometric (photospheric) and spectroscopic (chromospheric) variations is essential for identifying the cause of Doppler shifted absorption lines in more active stars. These results were reported by Paulson *et al.* (2003a).

We have also conducted a differential abundance analysis of our Hyades F-K dwarfs to search for evidence of stellar enrichment from accreted hydrogen deficient disk material (Paulson *et al.* 2003b). We derived a cluster mean  $[\text{Fe}/\text{H}] = 0.13 \pm 0.01$ . Two stars showed abundances  $\sim 0.2$  dex larger than the cluster mean. Additionally, one star, which was added by a recent study as a cluster member, showed significantly lower abundances than the cluster mean. These three stars had questionable membership characteristics. The remaining stars in the survey had an rms of 0.04 dex in the differential  $[\text{Fe}/\text{H}]$  values. The Hyades cluster members have apparently not been significantly chemically enriched. The abundance ratios of Si, Ti, Na, Mg, Ca and Zn with respect to Fe are in their solar proportions.

We have now concluded our Hyades survey during this funding period. A few stars that are showing radial velocity variations that do not appear to be related to stellar activity are being monitored with the HET and VLT, and simultaneous photometry of these stars is being obtained with either the ROTSE automated photometric telescope. The HET is the ideal facility to use for this type of synoptic radial velocity monitoring.

## Hobby-Eberly Telescope Programs

### HET Radial Velocity Precision Achieved

The High Resolution Spectrograph (HRS) (Tull 1998) for the HET was built by a team headed by Robert Tull and Phillip MacQueen. This spectrograph was designed to be able to make stellar radial velocity variation measurements with a precision of  $3 \text{ m s}^{-1}$  or better on stars as faint as  $V = 10$ . The major key to being able to conduct an efficient and productive radial velocity search program is the radial velocity precision that can be achieved in a routine production mode. Many programs will quote a velocity precision achieved, and give one or two examples of stars showing this level of rms velocity scatter. However, the real demonstration of radial velocity precision is achieved from examination of the velocity rms achieved on the *entire* sample of stars observed. So far, we have observed 173 F-M dwarfs four or more times. Of all of these stars, 20 show large-amplitude variations indicative of previously unknown binary star systems, and 11 additional stars show rms variations greater than  $20 \text{ m s}^{-1}$ , but probably not large enough to be due to binary stellar companions. These stars represent good candidates for short-period planetary companions.

### A planetary companion to HD 37605.

During the one-year no-cost extension to this grant, we discovered a planetary-mass companion to HD 37605, one of the stars on our HET planet survey. HD 37605, a  $V = 8.69$  K0 dwarf, is quite typical of the stars in our HET program list. Our typical HET observing methodology is to obtain about 4-5 radial velocity measurements over the course of 1-2 weeks, in order to search for short-period “hot-Jupiter” RV variability. If a star appears stable on short timescales, it is then scheduled for less frequent observations in order to search for longer period orbits. The initial set of observations of HD 37605 were constant to within the observational error, but the next observation taken about one month later showed a decrease of about  $200 \text{ m s}^{-1}$ . This star was then put back into the queue at high priority for frequent observations. The HET then obtained spectra every 3-4 days during the decrease in radial velocity. We were easily able to fit a new orbital solution as the data became available from each night of HET observations. It quickly became obvious that the radial velocity minimum and periastron passage would occur just as the star was being lost from the HET observability window; the last HET data points would be obtained during twilight. It was critical to attempt to obtain nightly HET velocity measurements during this crucial orbital phase. The queue-scheduled operation of the HET enabled the crucial data to be obtained.

HD 37605 has a planetary-mass companion in a highly eccentric orbit. We obtain a period of  $54.2 \pm 0.2$  days, eccentricity of  $0.737 \pm 0.010$ , and a K velocity of  $262 \pm 5 \text{ m s}^{-1}$ . This gives a minimum companion mass of 2.84 Jupiter masses, and an orbital semi-major axis of 0.26 AU. The periastron distance of 0.0686 AU is large enough that we would not necessarily expect the orbit to be circularized in the age of the primary star. The rms residual of the HET/HRS data from the orbital solution is  $4.4 \text{ m s}^{-1}$ . From our radial velocity template spectrum (taken without the  $I_2$  cell), we derive an iron abundance of the primary star of  $[\text{Fe}/\text{H}] = 0.37$ , which makes HD 37605 a super-metal-rich star.

These observations of HD 37605 clearly demonstrate the power of the HET for this type of radial velocity survey. The telescope aperture and system sensitivity allow us to obtain excellent quality data on this  $V=8.7$  star. The queue scheduled operation of the telescope permits us to change our program priorities dynamically, and to obtain the data on critical targets *when the observations are most needed*. We did not need to wait until our next regularly scheduled observing run to obtain the necessary follow-up data. We simply reallocated our “Priority 1” observing time so that the HD 37605 observations would be at the top of the telescope queue. We communicated the importance of these observations to the HET operations staff, and they responded to accommodate our needs.

## Papers Published Under This Grant

1. "Search for planets around Hyades stars using the Keck telescope" (A. P. Hatzes and W. D. Cochran), *Proc. SPIE* **4005**, 252–259, 2000.
2. "Radial Velocity Searches for Extra Solar Planets from Keck and McDonald Observatories" (A. P. Hatzes and W. D. Cochran) in *From Extrasolar Planets to Cosmology: The VLT Opening Symposium*, J. Bergeron & A. Renzin Eds., Springer Verlag, 539, 2000.
3. "Evidence for a Long-period Planet Orbiting Epsilon Eridani" (A. P. Hatzes, W. D. Cochran, B. McArthur, S. L. Baliunas, G. A. H. Walker, B. Campbell, A. W. Irwin, S. Yang, M. Kürster, M. Endl, S. Els, R. P. Butler and G. W. Marcy), *Ap. J. Letters*, **544**, L145–L148, 2000.
4. "The planet search program at the ESO Coudé Echelle spectrometer. II. The  $\alpha$  Centauri system: limits for planetary companions" (M. Endl, M. Kürster, S. Els, A. P. Hatzes and W. D. Cochran) *Astronomy and Astrophysics* **374**, 675–681, 2001.
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6. "Searching for Planets in the Hyades I. The Keck Radial Velocity Survey" (W. D. Cochran, A. P. Hatzes and D. B. Paulson) *Astron. J.* **124**, 565–571, 2002.
7. "Searching for Planets in the Hyades II: Some Implications of Stellar Magnetic Activity" (D. B. Paulson, S. H. Saar, W. D. Cochran and A. P. Hatzes) *Astron. J.* **124**, 572–582, 2002.
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10. "Searching for ExtraSolar Planets With the Hobby-Eberly Telescope" (W. D. Cochran, R. G. Tull, P. J. MacQueen, D. B. Paulson, M. Endl and Artie P. Hatzes) in Proceedings of "Scientific Frontiers in Research on Extrasolar Planets", A.S.P. Conference Series, 294, 561, 2003.
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12. "Searching for Planets in the Hyades III: The Quest for Short-Period Planets" (D. B. Paulson, S. H. Saar, W. D. Cochran and G. W. Henry) *Astron. J.* **127**, 1644–1652, 2004.
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14. "The low-level RV variability in Barnard's star (=GJ 699). Secular acceleration, indications for convective redshift, and planet mass limits" (M. Kürster, M. Endl, F. Rouesnel, S. Els, A. Kaufer, S. Brilliant, A. P. Hatzes, S. H. Saar and W. D. Cochran) *Astronomy and Astrophysics* **403** 1077–1087, 2003.
15. "A Planetary Companion to  $\gamma$  Cephei A" (A. P. Hatzes, W. D. Cochran, M. Endl, B. McArthur, D. B. Paulson, G. A. H. Walker, B. Campbell, and S. Yang) *Ap. J.*, **599** 1383–1394, 2003.
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